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Research Article

Changes in landscape disturbance intensity of sloping land in mountainous areas and their relationship with ecosystem services

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Abstract

The stability of landscapes on sloping land forms the foundation for ecological protection and sustainable development in mountainous regions. However, with the intensification of human activities, particularly in the complex mountainous areas of southwest China, the landscape patterns on sloping land have been severely disrupted. This study examines the spatiotemporal changes in landscape disturbance intensity on sloping land in Guiyang and their impact on ecosystem services. The findings show that, over the past 20 years, the overall landscape disturbance intensity has generally decreased, particularly between 2000 and 2010. However, disturbance intensity has increased in certain gradient zones, such as areas with slopes between 20–25 degrees. Meanwhile, ecosystem services have generally declined, especially in water yield and crop production, while carbon stock has slightly increased. The study reveals a significant spatial correlation between landscape disturbance intensity and ecosystem services, with varying relationships across different services. It emphasises the profound impact of human activities on landscape stability and ecosystem services, particularly in areas with steeper slopes. The contribution of this research lies in providing a scientific basis for sustainable landscape management and ecosystem service conservation in mountainous areas, highlighting the importance of mitigating human disturbance and strengthening ecological restoration.

Key words: Correlation, ecosystem functions, landscape patterns, mountainous regions, spatial patterns

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Introduction

Landscape stability plays a crucial role in maintaining regional ecological stability, which is the basis for sustaining ecosystem services and achieving sustainable development (Zhang et al. 2022; Zhao et al. 2023). Although regional landscapes possess certain stability to disturbances (Wang et al. 2022), intensified human activities have dramatically altered landscape structures, sizes and quantities, thus affecting landscape stability and security (Huang et al. 2021). As a result of the coupling between human activities and the geographical environment, sloping land in mountainous areas has formed distinct spatiotemporal landscape patterns under varying ecological and historical conditions (Nagendra and Utkarsh 2003; Theissen et al. 2019). Under the influence of environmental changes and complex human activities, mountainous sloping land

has been heavily disturbed, posing severe threats to its ecological environment (Li et al. 2023a). Therefore, it is imperative to investigate changes in landscape patterns on sloping land and their ecological effects.

Landscape disturbance intensity refers to the severity of external disturbances affecting various landscape components, making it a key area of research in landscape ecology. Existing studies on landscape disturbance primarily focus on changes in landscape patterns under various disturbance factors (Yi et al. 2021; Wu et al. 2022), quantitative assessments of disturbance intensity (Sinha and Sharma 2006; Su et al. 2010) and the relationship between human interference and landscape evolution (Zhou et al. 2018; Wu et al. 2021). These disturbances include natural factors like wildfires, climate change and earthquakes (Peterson 2002; Seidl and Rammer 2017), as well as human activities, such as urban construction and agricultural practices (Signorelli et al. 2016; Wang et al. 2023a). Research has elucidated the characteristics of landscape disturbance, revealing close connections amongst disturbance types, intensity, duration and landscape patterns (Marull et al. 2015; Zhou et al. 2018). Landscapes such as forests, wetlands and agricultural lands are focal points in landscape disturbance studies (Solon 1995; Moore and Richardson 2012). Evaluation methods typically involve indicator construction and modelling, with spatial analysis being commonly used to analyse disturbance patterns. Studies have demonstrated that computer simulations can model natural disturbance patterns, aiding in understanding the mechanisms of landscape disturbance (Hunter 2007). Additionally, as landscape disturbance levels have changed dramatically in many regions, the environmental impacts of these disturbances have become a central research focus. Reduced human disturbance has been shown to stabilise landscape patterns in nature reserves, improving environmental quality (Zhang et al. 2014). Agricultural landscape disturbances have significant impacts on the richness of invasive species (Boscutti et al. 2018). Although substantial progress has been made in quantifying and assessing the impact of landscape disturbance, few studies have specifically examined complex mountainous areas with high levels of human activity. Moreover, research on the ecological effects of landscape disturbances often focuses on one aspect of the environment, with little coverage of the effects on multiple ecosystem services.

Southwest China is a region with severe conflicts between fragile ecosystems and intense human-nature interactions. This region has experienced frequent extreme weather events, rapid economic development, urbanisation and population growth, all within a sensitive and vulnerable ecosystem. Consequently, the region's landscape ecology has been intensely disturbed, with significant implications for the ecological environment (Pu et al. 2020; Wang and Dai 2020; Li et al. 2023a; Meng et al. 2023). Sloping land in this region is particularly vulnerable to human disturbances. In recent decades, various factors, including climate change, urbanisation, the West Development Strategy and ecological restoration efforts, have impacted landscape stability (Wang et al. 2021; Lin and Wang 2023; Sun et al. 2023). Although some researchers have focused on landscape patterns in southwest China's mountainous areas (Li et al. 2021; Wang et al. 2023b), there has been no specific research on the disturbance intensity of sloping land and its effects on ecosystem services. Therefore, this study selects Guiyang, a representative city in southwest China's mountainous region, to analyse changes in landscape disturbance intensity on

sloping land and its impact on ecosystem services. The findings aim to provide scientific guidance for optimising landscape patterns and protecting the ecological environment in mountainous regions.

Datasets and methods

Overview of the study area

Guiyang, the capital of Guizhou Province, is located in southwest China, between 26°11'–26°55'N, 106°07'–107°17'E, covering a total area of 8,043 km^2 (Fig. 1). The region's altitude ranges from 512 to 1,738 m, characterised by complex topography, with mountainous terrain being predominant and accounting for about 60% of the land area. Moreover, the area features typical karst landforms, with karst terrain covering 85.02% of the total land area. The region has a subtropical monsoon climate, with hot, rainy summers and concurrent rainfall and heat. The average annual temperature is approximately 15.2 °C and the average annual precipitation is around 1100 mm. The region has rich vegetation types, including evergreen broad-leaved forests, coniferous forests and grasslands, forming an important ecological barrier for the upper Yangtze and Pearl River watersheds. From 1990 to 2020, Guiyang's population increased by 3.138 million people and its GDP grew by 371.143 billion RMB. In recent years, global climate change and intense human interference have made this region's ecosystems highly vulnerable, with significant conflicts between population growth, resources and the environment, making it a globally recognised sensitive zone (Han et al. 2023).

Data sources

The data used in this study include land-use data, DEM data, climate data and soil data. The land-use data are derived from the raster data of land use in 2000, 2010 and 2020 (30 m resolution) provided by the Chinese Academy of Sciences. These data are based on Landsat remote sensing images, interpreted using a human-machine interactive visual method, classifying land use into six categories: cropland, forest land, grassland, waterbodies, construction land and unused land. Elevation data are sourced from the geospatial cloud platform (http://www.gscloud.cn/) with a spatial resolution of 30 m from the GDEM DEM data. Climate data include

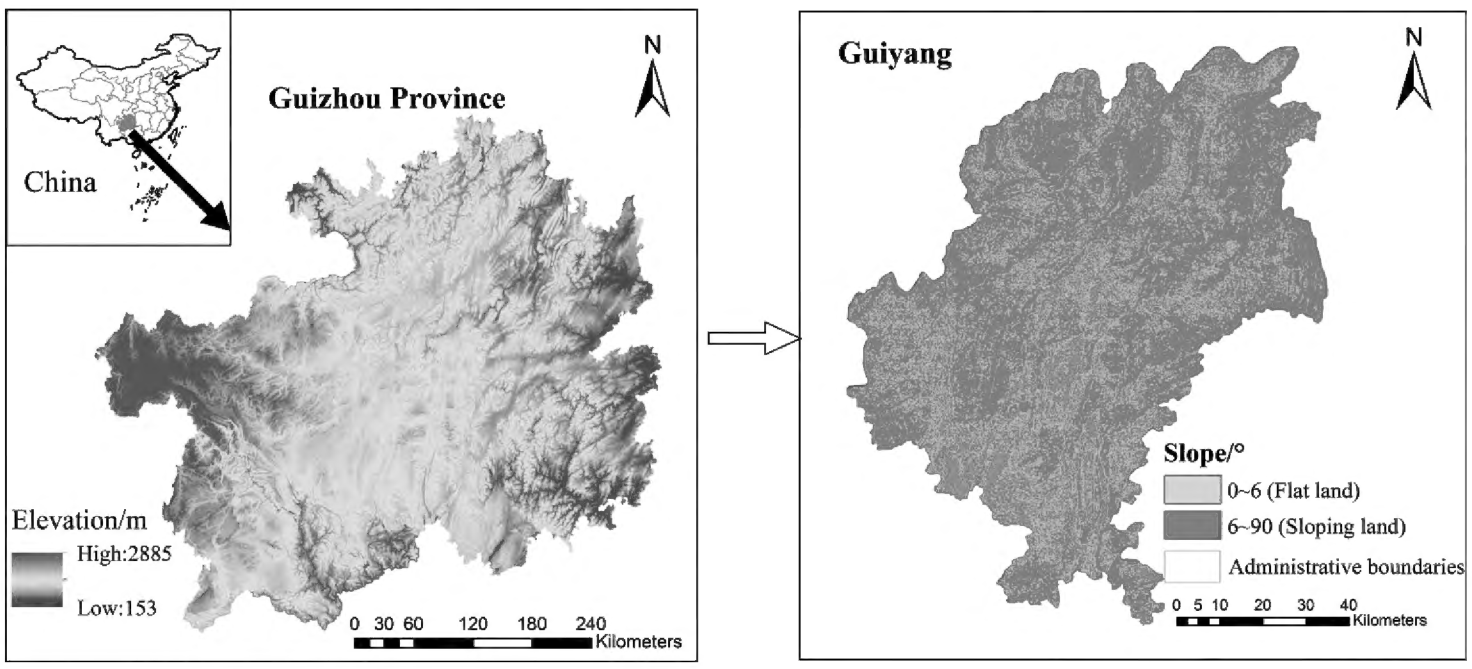

Figure 1. Location and distribution of sloping land in Guiyang, China.

daily observations from nine meteorological stations in Guiyang City from 2000 to 2020, provided by the Guizhou Climate Center. These data include daily precipitation, daily maximum temperature, daily minimum temperature, daily average temperature, relative humidity, absolute humidity, sunshine duration and wind speed. Soil data are from the China Soil Database, including soil texture and soil type.

Methods

Definition and spatial mapping of sloping land

Based on the characteristics of slope distribution in the study area and referencing relevant literature (Cai et al. 2018), a threshold of 6° was used to distinguish between sloping land and flat land. Land with a slope of 6° or greater is defined as sloping land. To explore the differences in landscape disturbance intensity and ecosystem services across different slope gradients, the slopes were classified into five categories: Gradient I (6°-10°), Gradient II (10°-15°), Gradient III (15°-20°), Gradient IV (20°-25°) and Gradient V (> 25°).

Calculation of landscape disturbance intensity

According to the principles of landscape ecology, landscape disturbance intensity is determined by landscape fragmentation, separation and dominance (Han et al. 2023). The calculation formulae for landscape disturbance intensity are as follows:

$$\mathbf{C}_{\mathrm{i}} = \boldsymbol{n}_i \;/\; \boldsymbol{A}_i \tag{1}$$

$$\boldsymbol{S}_i = 0.5\sqrt{\frac{\boldsymbol{n}_i}{\boldsymbol{A}}} / \frac{\boldsymbol{A}_i}{\boldsymbol{A}} \tag{2}$$

$$\boldsymbol{D}_i = 0.25\ (\boldsymbol{n}_i \;/\; \boldsymbol{N} + \boldsymbol{m}_i \;/\; \boldsymbol{M}) + 0.5\ \boldsymbol{A}_i \;/\; \boldsymbol{A} \tag{3}$$

$$\boldsymbol{U}_i = \boldsymbol{a} \cdot \boldsymbol{C}_i + \boldsymbol{b} \cdot \boldsymbol{S}_i + \boldsymbol{c} \cdot \boldsymbol{D}_i \tag{4}$$

where C_i represents landscape fragmentation, S_i represents landscape separation, D_i represents landscape dominance and U_i is the landscape disturbance intensity. n_i refers to the number of patches of landscape type i, A_i is the area of patches of landscape type i, A is the total area of the landscape, N is the total number of landscape patches, m_i is the number of grids where landscape type i occurs and M is the total number of grids. The weights for fragmentation, separation and dominance, denoted by a, b and c, respectively, are set, based on a comprehensive consideration of previous research (Sun et al. 2022) and the characteristics of the study area (severe landscape fragmentation due to terrain). As a result, fragmentation is considered the most important, followed by separation and dominance, with the weights assigned as 0.5, 0.3 and 0.2, respectively. n_i and A_i are calculated using Fragstats software.

Ecosystem services evaluation method

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is a tool used for evaluating ecosystem services, widely applied in environmental

management and spatial planning research. The model is based on a comprehensive approach integrating ecology, geographic information systems (GIS) and economics. It helps researchers and decision-makers understand the impact of different management measures on ecosystem services by simulating and quantifying the supply, demand and interrelationships of various ecosystem services. The core objective of this study is to assess the supply of ecosystem services in mountainous cities. Compared to other traditional ecological models, the InVEST model is characterised by high spatial accuracy, multi-service assessment and ease of use, making it particularly suitable for this research. The application process of the InVEST model in ecosystem service evaluation mainly includes steps, such as data input, model selection and setup and ecosystem service calculation. The validation of the InVEST model's calculation results is conducted by referencing Han's study (Gao et al. 2024). The selection of the five ecosystem services — Water yield, Soil retention, Carbon stock, Habitat quality and Crop production — in the ecosystem service evaluation covers the key supporting functions of the ecosystem in the study area related to water, soil, carbon, biodiversity and agricultural production. This selection comprehensively reflects the multiple contributions of ecosystem services to the region's sustainable development.

(1) Water yield

The InVEST model's water yield module is used to calculate water yield.

$$W = (1 - \frac{E_i}{P_i}) \cdot P_i \tag{5}$$

where W is water yield, P_i is annual precipitation and E_i is actual evapotranspiration.

(2) Soil retention

Soil retention is estimated using the soil loss equation.

$$SC = R \cdot K \cdot LS \cdot (1 - C \cdot P) \tag{6}$$

where SC is soil retention, R is rainfall erosivity, K is soil erodibility, LS is slope length and steepness, C is vegetation cover and P is conservation practices. The parameters for these two factors (C and P) are primarily determined, based on the research by Han et al. (2019).

(3) Carbon stock

Carbon stock is calculated, based on land-use data and carbon density of various land use types:

$$C_i = \sum (C_{above} + C_{below} + C_{soil} + C_{dead}) \cdot F_i \tag{7}$$

where C_t represents carbon stock, C_{above},C_{below},C_{soil} and C_{dead} refer to the carbon densities of aboveground vegetation, belowground vegetation, soil and dead organic matter, respectively. F_i denotes the area of land-use type *i*. The carbon density values are primarily based on the research findings of He et al. (2024).

(4) Habitat quality

Habitat quality is assessed using the habitat quality module of the InVEST model. This module generates habitat quality maps, based on land-use type data, considering the relative impact of each threat factor on habitat, the distance between threats and habitat grids and other biodiversity threat factors:

$$Q_{xj} = H_j(1 - \frac{D_{xj}^z}{D_{xj}^z} + k^z) \quad (8)$$

where Q_{xj} is the habitat quality index for grid x in habitat type j. D_{xj} is the overall threat level for grid x in habitat type j. z and k (semi-saturation parameters) are proportional factors, usually fixed constants. Parameters for this module are primarily based on the methods of Han et al. (2022).

(5) Crop production

Crop production is calculated, based on the cultivated area and yield data for each district:

$$G = Q \cdot V \quad (9)$$

where G represents crop production. Q is the crop yield per unit area for each administrative district. V is the cultivated area. Crop yield data are sourced from the annual statistical yearbooks of Guiyang.

Spatial analysis methods for landscape disturbance intensity and ecosystem services

To better guide landscape optimisation and ecosystem service management in each administrative region, landscape disturbance intensity and ecosystem services for sloping land within the town-scale administrative regions of Guiyang were calculated. The results were imported into ArcGIS software to obtain spatial patterns of landscape disturbance intensity and ecosystem services for sloping land. Finally, using ArcGIS spatial analysis tools, the spatial changes in landscape disturbance intensity and ecosystem services for the periods 2000–2010, 2010–2020 and 2000–2020 were computed.

Analysis of the relationship between landscape disturbance and ecosystem services

Using spatial analysis tools, the results of ecosystem service assessments can be integrated with the spatial distribution of landscape disturbances for detailed spatial analysis and visualisation, further revealing the specific impacts of landscape changes on ecosystem services. Based on the results of landscape disturbance intensity and ecosystem services at the town scale, spatial autocorrelation analysis methods provided by GeoDa software (Moran's I and LISA maps) were used to analyse whether there is spatial correlation between landscape disturbance intensity and ecosystem services at the town scale. The calculation method is as follows:

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} w_{ij} \left(x_i - x_m\right) \left(x_j - x_m\right) / \sum_{i=1}^{n} \sum_{j=1}^{m} w_{ij}}{\sum_{i=1}^{n} \left(x_i - x_j\right) / n} \tag{10}$$

where I is the Moran's I index; x_i is the value for unit i; x_j is the value for unit j; x_m is the mean value of the unit; w_{ij} is the coefficient; and n is the total number of evaluation units. Moran's I ranges from -1 to 1. When Moran's I is close to 1, it indicates a positive spatial correlation; when it is close to -1, it indicates a negative spatial correlation; and when it is close to 0, it indicates no significant spatial autocorrelation.

LISA maps reflect the spatial autocorrelation level of Moran's I, classifying the study area into five types: high-high, high-low, low-low, low-high and non-significant. High-high and low-low indicate positive local spatial correlation, while low-high and high-low indicate negative local spatial correlation.

Using the spatial analysis tools in ArcGIS software, the correlation between landscape disturbance intensity and ecosystem services across different slope gradient zones was analysed. This method is based on two different layers, with correlation analysis performed using Pearson's coefficient. Specifically, landscape disturbance intensity and ecosystem service data at the raster scale were clipped for each slope gradient zone. Subsequently, Pearson's coefficient was calculated using the Multivariate analysis method in ArcGIS software to determine the correlation between landscape disturbance intensity and ecosystem services.

Results

Changes in landscape disturbance intensity of sloping land

Over the past 20 years, the overall landscape disturbance intensity of sloping land has shown a decreasing trend, with a more pronounced decline from 2000 to 2010 compared to the period from 2010 to 2020. Considering different gradients, the landscape disturbance intensity in Gradients I, II, III and V decreased between 2000 and 2020, while Gradient IV exhibited an increasing trend. The decline in Gradient I was greater than that in the other gradients during the same period. Specifically, the decline in Gradient I was more significant from 2010 to 2020 than from 2000 to 2010. In Gradients II and III, the disturbance intensity increased from 2000 to 2010 and decreased from 2010 to 2020, respectively. For Gradient IV, the landscape disturbance intensity increased during both 2000–2010 and 2010–2020. For Gradient V, the decline from 2000 to 2010 was greater than that from 2010 to 2020 (Table 1).

Table 1. Changes in landscape disturbance intensity of sloping land.

Region	2000	2010	2020	2000–2010	2010–2020	2000–2020
Gradient I	5.82	5.77	5.20	-0.05	-0.56	-0.62
Gradient II	5.62	5.76	5.13	0.14	-0.63	-0.49
Gradient III	5.27	5.55	5.24	0.27	-0.30	-0.03
Gradient IV	5.05	5.24	5.35	0.19	0.11	0.31
Gradient V	5.12	4.81	4.69	-0.31	-0.12	-0.43
All sloping land	5.61	5.51	5.50	-0.09	-0.01	-0.10

In 2000 and 2010, the spatial patterns of landscape disturbance intensity of sloping land were relatively similar. High disturbance intensity areas were primarily located in the central-northern and western regions, while low disturbance intensity areas were mainly in the southern region. In 2020, high disturbance intensity areas were mainly concentrated in the northeast and south, while low disturbance intensity areas were primarily in the west and northwest (Fig. 2).

Between 2000 and 2010, areas with increased landscape disturbance intensity on sloping land were mainly located in the northern and southern regions, while areas with decreased disturbance intensity were primarily in the western and central regions. From 2010 to 2020, most areas in the study region showed a decrease in landscape disturbance intensity, with only the southern and north-eastern regions being the primary areas of increased disturbance intensity. Between 2000 and 2020, the regions of decreased landscape disturbance intensity were mainly concentrated in the central, western and south-eastern areas, while the increased disturbance intensity areas were focused in the northern and central-southern regions (Fig. 3).

Changes in ecosystem services of sloping land

In the past 20 years, the ecosystem services of sloping land — namely water yield, soil retention, habitat quality and crop production — have shown a decreasing trend, with the exception of carbon stock, which has increased. The decline in water yield between 2000 and 2010 was more significant than between 2010 and 2020, while the decline in crop production between 2000 and 2010 was less pronounced

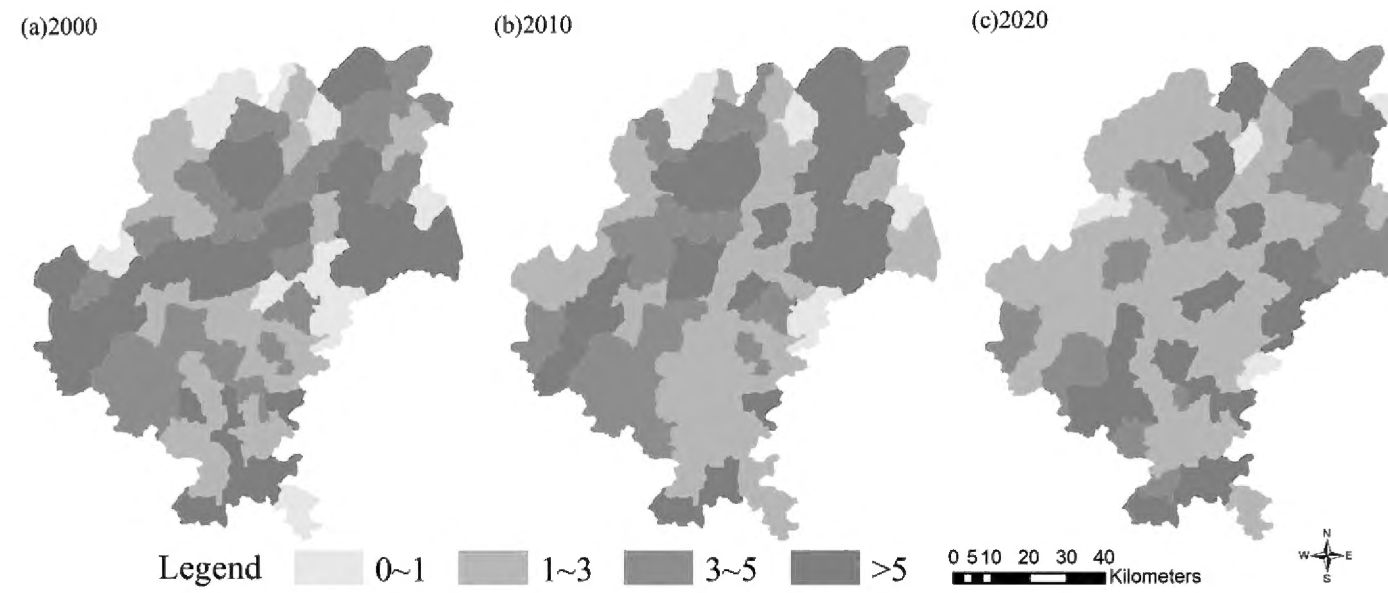

Figure 2. Spatial patterns of landscape disturbance intensity of sloping land in 2000, 2010 and 2020.

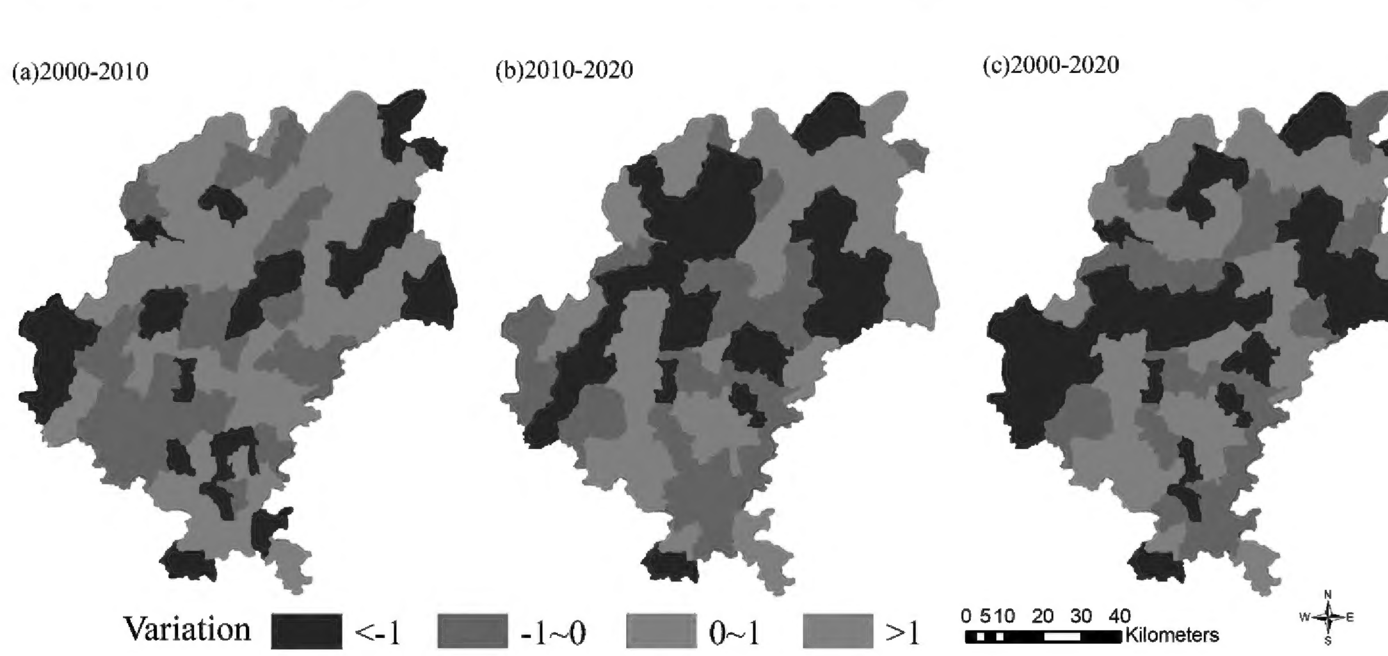

Figure 3. Spatial patterns of changes in landscape disturbance intensity of sloping land.

Table 2. Overall changes in ecosystem services of sloping land.

Service Type	2000	2010	2020	2000–2010	2010–2020	2000–2020
Water yield	458196	379025	350319	-79171	-28706	-107877
Soil retention	213548	170149	180795	-43399	10646	-32753
Carbon stock	163584	164965	163604	1381	-1361	20
Habitat quality	0.6508	0.6559	0.6471	0.0051	-0.0088	-0.0037
Crop production	554.92	552.80	534.70	-2.11	-18.10	-20.22

Note: Water yield is in thousand m^3; Soil retention, carbon stock and crop production are in thousand tonnes; Habitat quality is dimensionless.

compared to 2010–2020. Soil retention showed a decreasing trend from 2000 to 2010 and an increasing trend from 2010 to 2020. Carbon stock and habitat quality increased between 2000 and 2010, but decreased between 2010 and 2020 (Table 2).

In 2000, 2010 and 2020, water yield, carbon stock and crop production decreased progressively from Gradient I to Gradient V, while habitat quality increased from Gradient I to Gradient V. Soil retention was highest in Gradient II, followed by Gradient I, while Gradients III, IV and V had lower values. From 2000 to 2020, water yield and crop production continuously decreased across all gradients, while soil retention showed a pattern of decrease followed by an increase. Carbon stock in all gradients increased first and then decreased from 2000 to 2020. Similarly, except for Gradient V, habitat quality in other gradients exhibited a pattern of increase followed by decrease over the past 20 years (Fig. 4).

In 2000, 2010 and 2020, high-value areas for water yield and carbon stock were concentrated in the northeast and southwest, while low-value areas were primarily in the southern region. High-value areas for soil retention were

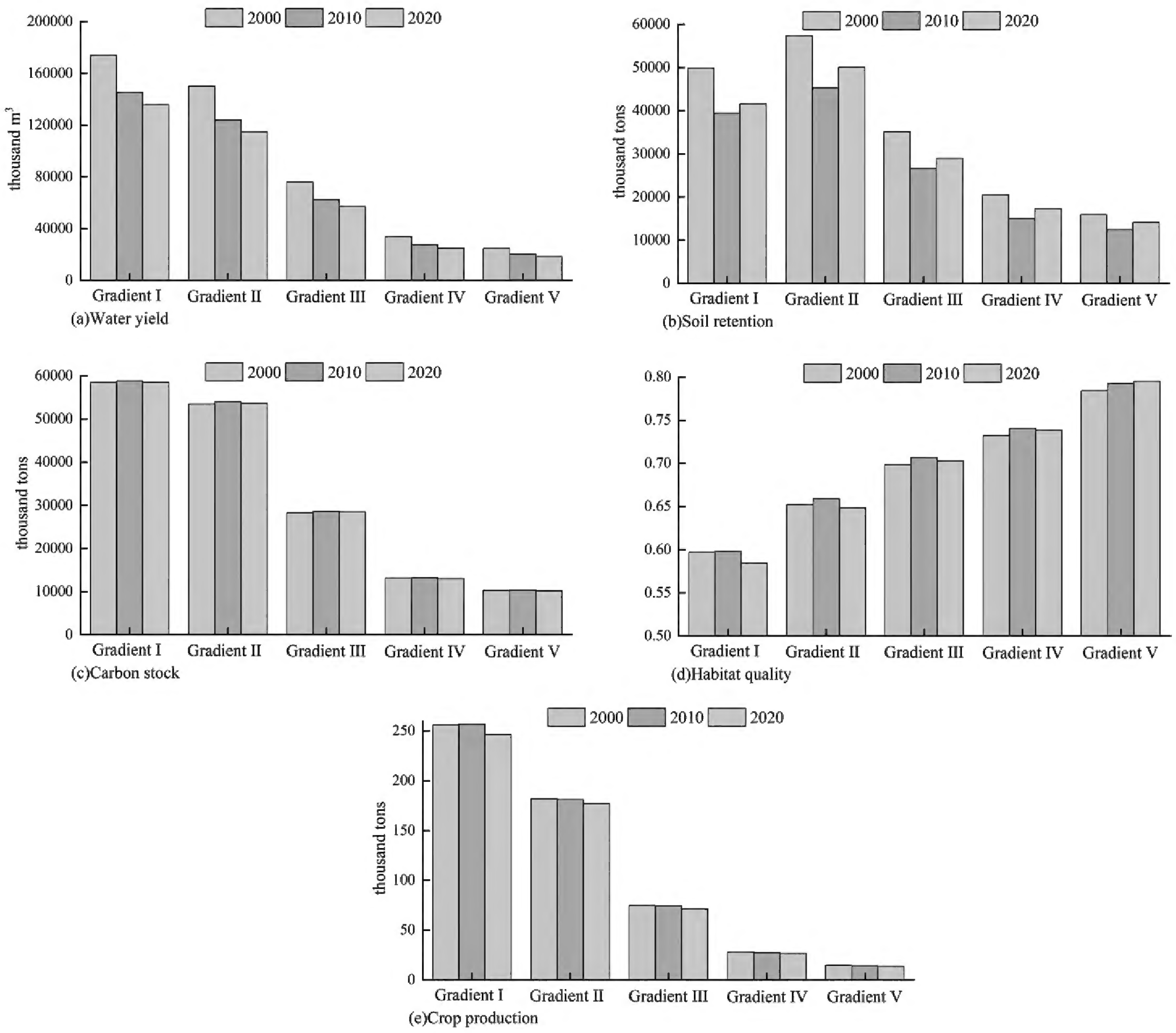

Figure 4. Changes in ecosystem services of sloping land across different gradients.

mainly in the north and sporadically in the west, with low-value areas predominantly in the central and southern regions. High-value areas for habitat quality were mainly in the central-northern part, while low-value areas were concentrated in the northwest, west and south. High-value areas for crop production were mainly in the northeast, northwest and west, with low-value areas primarily in the south and central regions (Fig. 5).

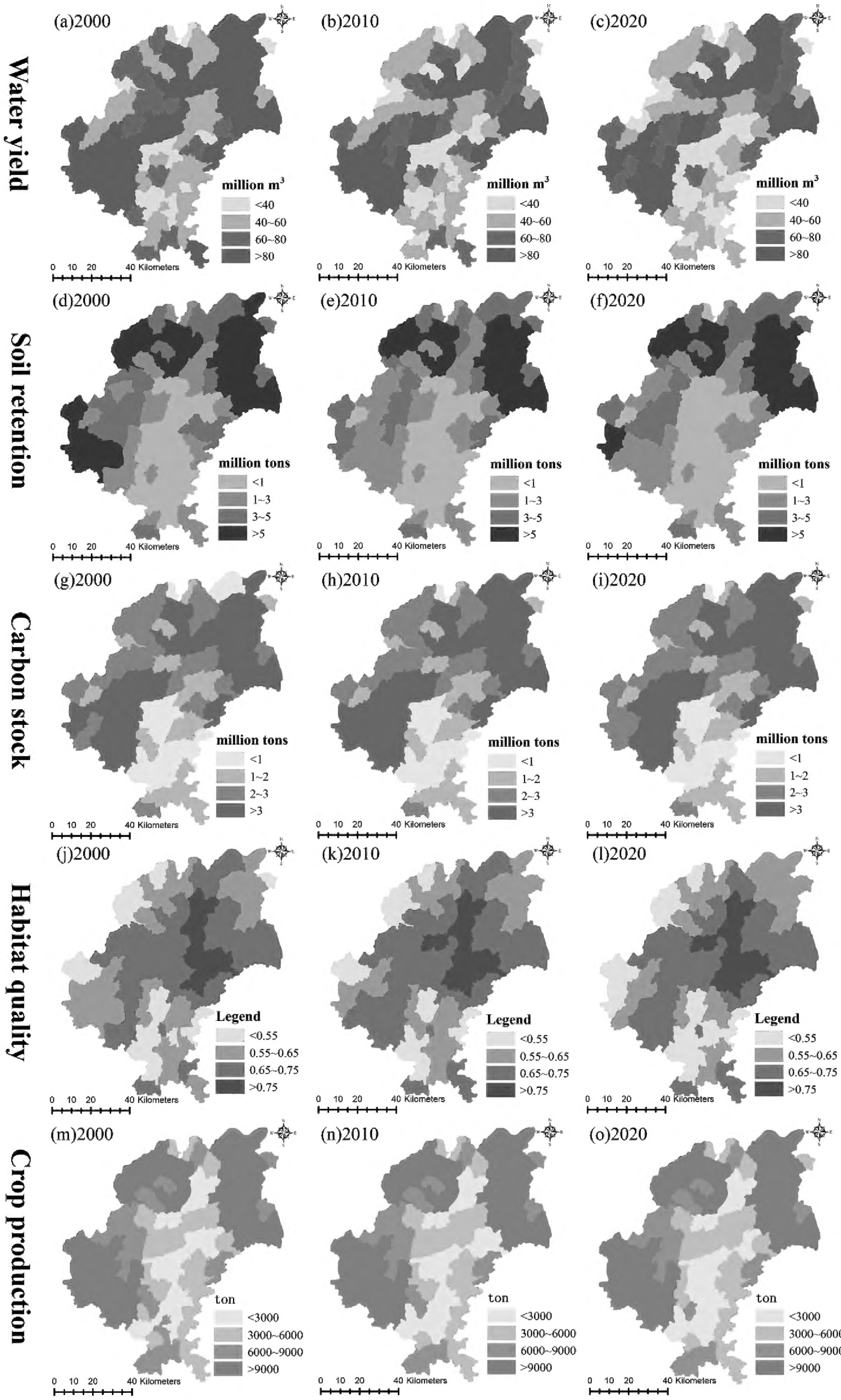

Figure 5. Spatial patterns of ecosystem services of sloping land in 2000, 2010 and 2020.

From 2000 to 2010, 2010 to 2020 and 2000 to 2020, water yield showed a decreasing trend in most areas of the study region, with only a few areas in the northwest, west and central regions showing an increase during 2010–2020. Soil retention exhibited a decreasing trend in most areas of the study region from 2000 to 2010 and from 2000 to 2020, but increased in most areas from 2010 to 2020, with notable increases in the northeast, southwest and southern regions. Carbon stock generally increased from 2000 to 2010 in most areas, except for sporadic regions in the north and west, but showed a decrease from 2010 to 2020 in most areas. From 2000 to 2020, carbon stock decreased in the northeast, west and south, while other regions showed an increase. Habitat quality increased in most areas from 2000 to 2010, but decreased in most areas from 2010 to 2020. Habitat quality increased in the northeast and central-western regions from 2000 to 2020, but decreased in the northwest, west and south. Crop production showed a decreasing trend in most areas from 2000 to 2010, 2010 to 2020 and 2000 to 2020, with the most notable decline in the south. Only the north and central regions saw an increase in crop production (Fig. 6).

Correlation between landscape disturbance intensity and ecosystem services on sloping land

There was a positive correlation between landscape disturbance intensity and water yield in 2000 and 2010, but a negative correlation in 2020. A positive correlation was observed between landscape disturbance intensity and soil retention, carbon stock and crop production in 2000, 2010 and 2020. Conversely, a negative correlation was found between landscape disturbance intensity and habitat quality in all three years. Throughout 2000–2010, 2010–2020 and 2000–2020, landscape disturbance intensity consistently showed a negative correlation with water yield. Except for 2000–2020, the other two periods showed a negative correlation between landscape disturbance intensity and soil retention. The relationship between landscape disturbance intensity and carbon stock was positive in the periods other than 2010–2020. While there was a negative correlation between landscape disturbance intensity and habitat quality from 2000 to 2010, a positive correlation was observed during 2010–2020 and 2000–2020. A positive correlation was present between landscape disturbance intensity and crop production in all three periods (Table 3).

In 2000, 2010 and 2020, high-high and low-high zones for landscape disturbance intensity versus water yield, carbon stock and crop production were mainly located in the northeast and southwest, while low-low and high-low zones were concentrated in the southern region. High-high and low-high zones

Table 3. Moran's I for the correlation between landscape disturbance intensity and ecosystem services on sloping land.

Service Type	2000	2010	2020	2000–2010	2010–2020	2000–2020
Water yield	0.3033	0.4061	-0.1185	-0.2007	-0.0233	-0.0231
Soil retention	0.1563	0.4181	0.2916	-0.1401	-0.6864	0.2596
Carbon stock	0.1557	0.5837	0.1716	0.0426	-0.6537	0.4865
Habitat quality	-0.4266	-0.6551	-0.3525	-0.1729	0.0563	0.2495
Crop production	0.5369	0.3670	0.4969	0.2211	0.3583	0.1638

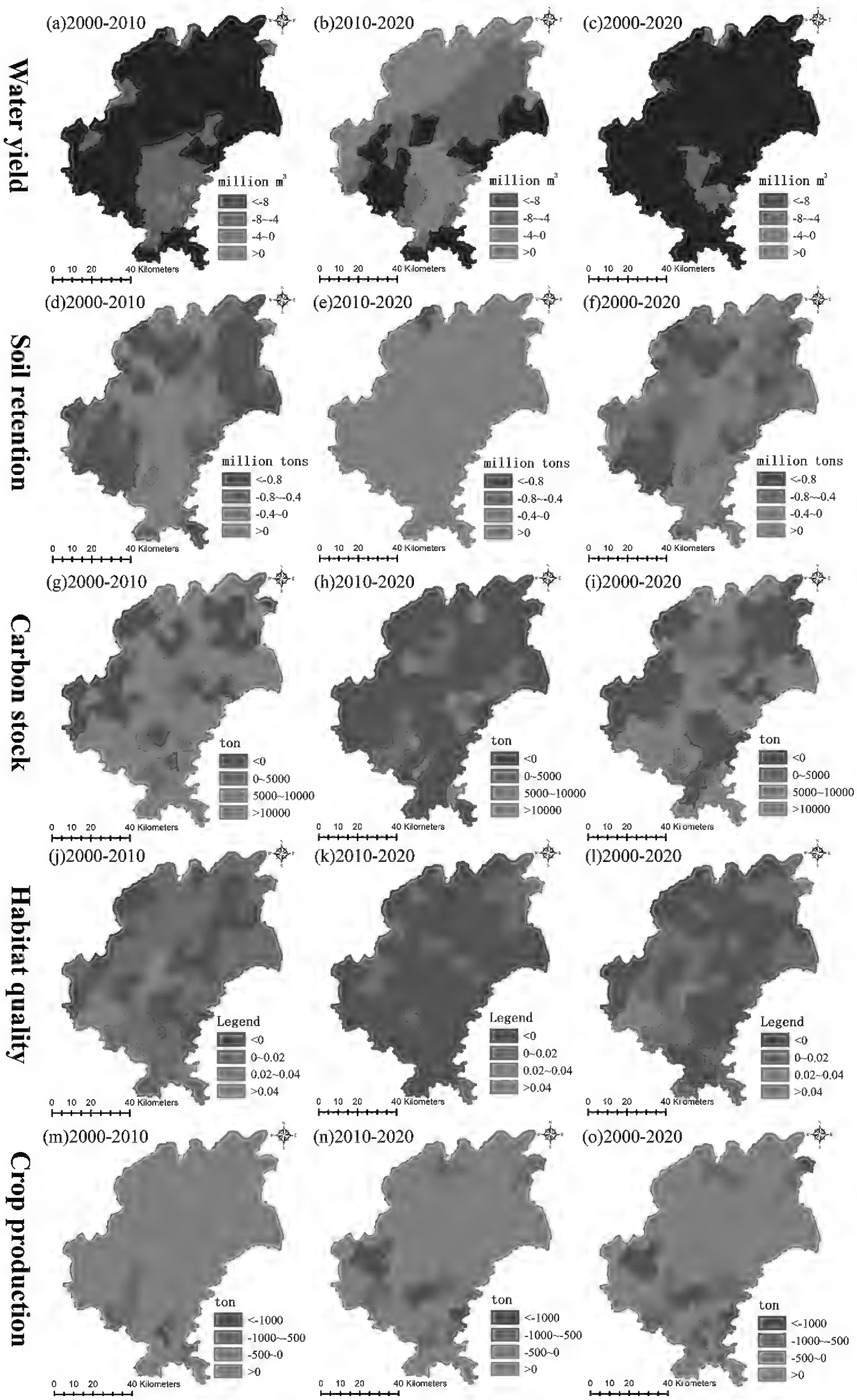

Figure 6. Spatial patterns of changes in ecosystem services of sloping land.

for landscape disturbance intensity versus soil retention were mainly found in the northeast and northwest, while low-low and high-low zones were located primarily in the south. High-high and low-high zones for landscape disturbance intensity versus habitat quality were concentrated in the central region, while low-low zones were focused in the southwest (Fig. 7).

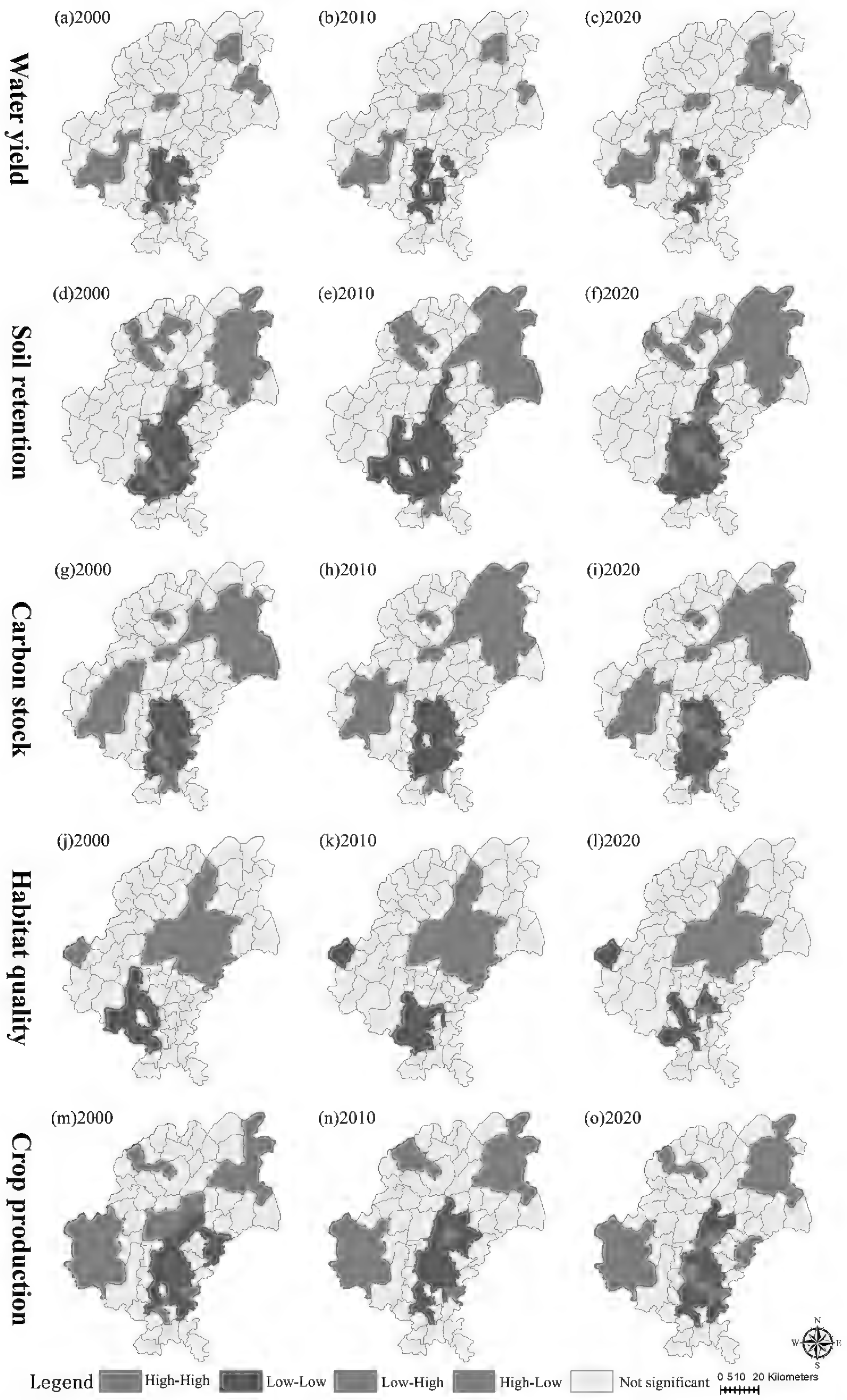

Figure 7. LIAS maps of the relationship between landscape disturbance intensity and ecosystem services on sloping land for 2000, 2010 and 2020.

Between 2000–2010 and 2000–2020, the high-high and low-high zones for the relationship between landscape disturbance intensity and water yield were primarily distributed in the southern region, while the low-low and high-low zones were mainly found in the southwest and northeast. In contrast, during 2010–

2020, high-high and low-high zones were mainly located in the northwest and low-low and high-low zones were concentrated in the southwest (Fig. 8a–c). During 2000–2010 and 2000–2020, high-high and low-high zones for landscape disturbance intensity versus soil retention were mainly distributed in the central

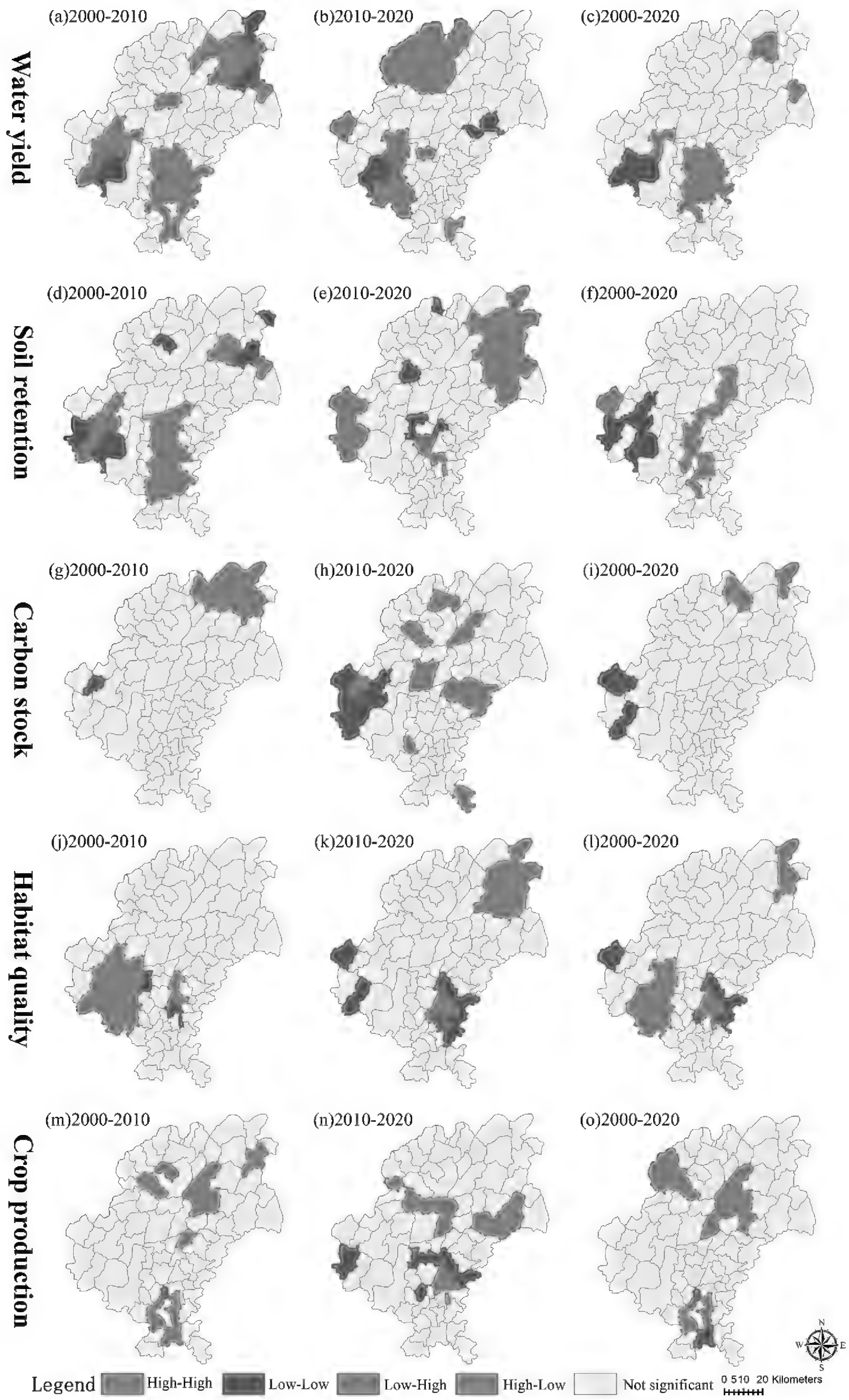

Figure 8. LIAS maps of the relationship between landscape disturbance intensity and ecosystem services on sloping land from 2000 to 2020.

and southern regions, while low-low and high-low zones were found primarily in the southwest. In 2010–2020, high-high and low-high zones were mainly located in the northeast and southwest, with low-low and high-low zones in the central and southern regions (Fig. 8d–f). Except for the low-low zones, high-high, low-high and high-low zones for landscape disturbance intensity versus carbon stock in 2000–2010 were concentrated in the northeast. During 2010–2020, high-high and low-high zones were mainly found in the central and southern regions, while low-low and high-low zones were located in the southwest. From 2000–2020, high-high and low-high zones were primarily in the north and low-low zones were mainly in the west (Fig. 8g–i). High-high and low-high zones for landscape disturbance intensity versus habitat quality in 2000–2010 were concentrated in the southwest, while low-low and high-low zones were in the central and southern regions. During 2010–2020, high-high and low-high zones were concentrated in the northeast and low-low and high-low zones were found in the southern and western regions. From 2000–2020, high-high and low-high zones were primarily in the northeast and southwest and low-low and high-low zones were in the southern and western regions (Fig. 8j–l). For landscape disturbance intensity versus crop production, high-high and low-high zones were mainly in the central and northern regions in 2000–2010 and 2000–2020, while low-low and high-low zones were in the south. During 2010–2020, low-high zones were mainly in the central region and low-low and high-low zones were found in the south and west (Fig. 8m–o).

Except for 2020, the relationship between landscape disturbance intensity and water yield was positive across gradient levels in 2000 and 2010. The relationships between landscape disturbance and soil retention, carbon stock and crop production showed positive correlations across gradient levels in 2000, 2010 and 2020, while landscape disturbance intensity and habitat quality exhibited negative correlations. Excluding Gradient IV, the relationships between landscape disturbance intensity and water yield were negative across gradient levels during 2000–2010, 2010–2020 and 2000–2020, while the relationship with crop production was consistently positive. Between 2000–2010 and 2010–2020, the correlation between landscape disturbance intensity and soil retention was negative across gradient levels (except for gradient IV), but it showed a positive correlation during 2000–2020. The relationship between landscape disturbance intensity and carbon stock was positive across gradient levels (except for gradient IV) in 2000–2010 and 2000–2020. Landscape disturbance intensity and habitat quality showed positive correlations in all gradient levels (except for gradient IV) (Table 4).

Discussion

Comparison with existing research and analysis of causes

The core of this study is to analyse changes in landscape disturbance intensity and their impact on ecosystem services in mountainous slope areas, with a focus on Guiyang, a typical karst region in south-western China. We found that landscape disturbance has generally declined over the past 20 years, particularly in lower gradient areas (Gradient I and Gradient II). At the same time, ecosystem services (except for carbon stock) also show a general trend of degradation. Existing research often categorises the main drivers of landscape disturbance into natural disturbances (such as wildfires and climate change)

Table 4. Correlation coefficients between landscape disturbance intensity and ecosystem services across different gradient levels.

Service types	Gradient levels	2000	2010	2020	2000–2010	2010–2020	2000–2020
Water yield	Gradient I	0.0176	0.0033	-0.0813	-0.1358	-0.0813	-0.2419
	Gradient II	0.1176	0.0734	-0.0220	-0.1910	-0.0857	-0.3035
	Gradient III	0.2550	0.1391	-0.0998	-0.1720	-0.0996	-0.2249
	Gradient IV	0.3451	0.2564	-0.0176	0.2016	0.1385	0.2883
	Gradient V	0.1019	0.3420	-0.3220	-0.1977	-0.0390	-0.5609
Soil retention	Gradient I	0.0137	0.0341	0.0106	-0.0062	-0.0172	0.0062
	Gradient II	0.0218	0.0274	0.0191	-0.0351	-0.0118	0.0321
	Gradient III	0.0536	0.0254	0.0137	-0.0618	-0.0284	0.0269
	Gradient IV	0.0306	0.0243	0.0216	0.0425	0.0096	-0.0047
	Gradient V	0.0440	0.0073	0.0439	-0.0068	-0.0483	0.0482
Carbon stock	Gradient I	0.0697	0.2068	0.0694	0.0934	-0.1002	0.3201
	Gradient II	0.1438	0.2288	0.1526	1.6440	-0.1010	0.3936
	Gradient III	0.0874	0.1577	0.1677	0.1791	-0.0042	0.1786
	Gradient IV	0.1731	0.4901	0.3667	-0.1069	0.0249	-0.2089
	Gradient V	0.1886	0.5839	0.4523	0.2595	-0.0726	0.5841
Habitat quality	Gradient I	-0.1266	-0.4300	-0.1126	0.0030	0.0450	0.1518
	Gradient II	-0.4344	-0.5886	-0.3438	0.0886	0.0100	0.3726
	Gradient III	-0.2488	-0.3928	-0.4490	0.0148	0.0596	0.2414
	Gradient IV	0.0494	-0.6610	-0.6930	-0.0338	-0.0070	-0.4588
	Gradient V	-0.6912	-0.7122	-0.2002	0.3028	0.1010	0.5716
Crop production	Gradient I	0.3473	0.2591	0.2132	0.1820	0.0613	0.0781
	Gradient II	0.3577	0.2510	0.2460	0.1581	0.0510	0.0712
	Gradient III	0.3280	0.2633	0.2791	0.1610	0.0466	0.0307
	Gradient IV	0.3219	0.2819	0.3203	-0.1663	-0.0287	-0.0296
	Gradient V	0.4109	0.2984	0.3216	0.1562	0.0283	0.0939

and human activities (such as urban expansion and agricultural activities) (Seidl and Rammer 2017; Wang et al. 2023a). This study reveals that in Guiyang's complex mountainous terrain, the combined effects of climate change and human activities have severely impacted slope landscape stability. Especially in areas with intense human activities, landscape fragmentation and separation have increased, leading to higher disturbance levels in certain gradient zones (e.g. Gradient IV). This is consistent with the findings of Li et al. (2023b), which indicate that landscape patterns are more prone to disturbance under rapid urbanisation and economic development.

The uniqueness of this study lies in its detailed analysis of landscape disturbance across different gradient zones. Existing research typically focuses on broad trends or specific disturbances (Rammer et al. 2024), whereas this study specifically examines how disturbance intensity varies across different gradient zones (from Gradient I to Gradient IV). This fine-grained analysis provides a more localised understanding of disturbance dynamics and enriches our knowledge of how topographical gradients influence landscape stability, especially in regions like Guiyang, which exhibit varying human activity intensities and ecological vulnerability.

The declining trend in landscape disturbance intensity observed in this study contrasts with the findings of Zhang et al. (2021), who noted that, in natural reserves, reduced human activities have led to stabilised landscape patterns. The decrease in disturbance in the study area is partly attributed to Guiyang's

increased efforts in ecological protection, including large-scale vegetation restoration and ecological management projects (Li et al. 2024). However, despite these measures, disturbance levels remain high in some higher-gradient and frequently disturbed areas (e.g. Gradient IV), suggesting limitations in the effectiveness of these interventions.

Policy recommendations

Policy recommendations and discussion

The findings of this study highlight that, despite significant advancements in ecological protection in Guiyang in recent years, certain areas, particularly those in higher gradient regions, continue to experience elevated levels of landscape disturbance. These areas not only show considerable disturbance, but also significant degradation in ecosystem services, such as water yield and soil retention. In light of these findings, this study proposes several policy recommendations aimed at mitigating disturbances and improving ecological stability.

The results indicate that regions such as Gradient IV and V, where disturbances are particularly high, require prioritised ecological restoration efforts. These areas have been identified as crucial for the preservation of essential ecosystem services, including water yield and soil retention, which are severely impacted by the ongoing disturbances. To address this, it is recommended to adopt targeted ecological restoration strategies, such as increasing vegetation cover and actively reducing human interventions, particularly agricultural expansion and urban development, in these sensitive areas. Moreover, restoration measures should integrate both ecological and socio-economic considerations to minimise the impact of these interventions on local communities. Guiyang faces a critical challenge in balancing its growing urbanisation with the need to protect its vulnerable landscapes. The results of this study emphasise the importance of considering the vulnerability of slope landscapes when formulating land-use policies. Future land-use planning should aim to limit development in high-gradient areas, prioritising ecological preservation over development in these regions. More specifically, the development of a zoning system could be introduced, which designates areas for intensive development, areas for conservation and areas where sustainable land-use practices, such as agroforestry, could be implemented. This zoning system should be aligned with landscape disturbance levels and ecosystem service needs to ensure that both ecological protection and economic development can be achieved harmoniously. Ecosystem services are essential indicators of the overall health of the landscape. The findings suggest that a more robust monitoring and assessment system is required to evaluate changes in these services and to measure the effectiveness of current ecological policies. The implementation of advanced monitoring tools, such as remote sensing technology and big data methods, would enable the government to regularly track changes in key ecosystem services, such as carbon storage, water yield and soil retention. These data would not only help in assessing the effectiveness of ecological management, but also allow for the adaptation of policies in response to emerging environmental trends. Regular ecosystem service assessments can provide actionable insights to refine and improve future land management strategies. Ecological protection must extend

beyond government efforts to engage the public and raise awareness about the importance of sustainable environmental practices. Public involvement in ecological restoration and conservation efforts can significantly enhance the success of these initiatives. The government should foster environmental awareness through targeted education campaigns and community outreach programmes. This could include promoting eco-friendly behaviour, such as waste reduction, water conservation and sustainable agricultural practices. Additionally, local communities can be actively encouraged to participate in ecological restoration projects, ensuring that these efforts are well-supported at the grassroots level. This will also foster a sense of shared responsibility for environmental stewardship, helping to build a more sustainable future for Guiyang.

Limitations and future research directions

Despite providing valuable insights into the changes in landscape disturbance and their impacts on ecosystem services, this study has several limitations. First, the temporal and spatial precision of the data used in this study could be improved. The land-use and climate data utilised are derived from datasets collected over different years. Although these datasets capture overall trends, they may not fully reflect the finer temporal and spatial scales of landscape disturbance and ecosystem service changes. Future studies could address this limitation by incorporating higher-resolution data, such as frequent remote sensing imagery and more granular climate model data, to enhance the temporal and spatial accuracy of the analysis. Second, there is inherent uncertainty in the model parameters used for assessing landscape disturbance and ecosystem services. The models, such as the InVEST model, rely on parameters that may vary across different regions. While substantial literature was referenced to determine these parameters (e.g. Han et al. (2023); He et al. (2024)), their selection still involves a degree of uncertainty, which could impact the accuracy of the results. Future research could refine the model parameterisation by conducting region-specific calibrations and incorporating more localised data, which would reduce uncertainty and improve the reliability of the findings. Finally, this study primarily focuses on key ecosystem services, such as water yield, soil retention and carbon stock. However, other critical ecosystem services, such as climate regulation and recreational benefits, were not thoroughly explored. Future research could expand the scope by including a broader range of ecosystem services to provide a more comprehensive assessment of how landscape disturbances affect various aspects of ecosystem functioning.

Building upon the limitations identified, future research could focus on several key areas. To overcome the temporal and spatial precision limitations, future studies could integrate real-time remote sensing data and high-resolution spatial datasets. This would allow for more accurate monitoring of landscape disturbances and ecosystem service changes over shorter time intervals, thus improving the overall understanding of these dynamic processes. In addition, more in-depth calibration of model parameters specific to local conditions should be conducted. Incorporating diverse data sources and applying sensitivity analysis would help identify the most influential parameters, thereby reducing uncertainty in model predictions. Another important direction for future research is expanding the scope of ecosystem

services assessments. Including aspects such as climate regulation, biodiversity and recreational services would provide a more holistic view of the relationship between landscape disturbances and ecosystem health. This approach could contribute to better-informed land-use and conservation policies. Lastly, integrating socioeconomic factors into future studies would enable a deeper understanding of how human activities interact with landscape disturbances and ecosystem services. Investigating the impacts of population density, land-use policies and economic development on ecosystem service provision would offer a more integrated approach to ecosystem management, further enhancing the sustainability of ecological systems.

Innovations

Despite the aforementioned limitations, this study has the following innovations:

(1) Multi-gradient analysis of landscape disturbance

Unlike most studies that analyse overall landscape disturbance, this study analyses changes in landscape disturbance through gradient zones (e.g. Gradient I to V). This multi-gradient approach reveals differences in landscape disturbance across various gradient levels, providing a more detailed reference for mountainous landscape management and ecological governance.

(2) Spatial correlation analysis of landscape disturbance and ecosystem services

Through spatial autocorrelation analysis (Moran's I and LISA maps), this study not only reveals changes in the spatial patterns of landscape disturbance, but also explores its spatial correlation with ecosystem services. This spatial analysis method helps identify key protection areas and provides theoretical support for the precise implementation of ecological restoration measures.

(3) Case study of complex mountainous regions

Most existing research focuses on plain areas or specific nature reserves, while this study selected the complex karst mountainous region in south-western China as the research subject. It analysed the dual impact of human activities on slope landscapes and ecosystem services. Such research in complex terrain areas is relatively rare, thus filling a knowledge gap in this field.

Conclusions

This study analyses changes in landscape disturbance intensity and ecosystem services in sloping lands to reveal the profound impact of human activities on mountainous slope landscapes and ecosystems over the past 20 years. The research indicates that, from 2000 to 2020, the overall landscape disturbance intensity in Guiyang City showed a declining trend, though significant differences were observed across different gradients. Gradients I and V experienced the most notable decrease in landscape disturbance intensity, whereas Gradient IV exhibited an increasing trend. This reflects the concentration and intensity of

human activities in the region, particularly against the backdrop of intensified economic development and urbanisation.

Corresponding to the changes in landscape disturbance intensity, the ecosystem services of sloping lands displayed complex dynamic changes. Water yield and crop production continuously declined throughout the study period, indicating that slope agricultural productivity is under significant pressure from human activities. Meanwhile, soil retention decreased from 2000 to 2010, but showed a slight rebound from 2010 to 2020, suggesting that ecological management measures might have had some positive effects on soil and water conservation. However, the trends in carbon stock and habitat quality were more unstable; although carbon stock slightly increased from 2000 to 2010, it decreased in the subsequent decade. This indicates that the carbon stock capacity of slope landscapes is significantly influenced by changes in landscape structure and land use.

Further spatial analysis revealed a significant spatial correlation between landscape disturbance intensity and ecosystem services. Areas with high landscape disturbance intensity are typically associated with a reduction in ecosystem services. This phenomenon is particularly evident in the southern and central regions of Guiyang City, while the western and northern regions, with lower disturbance intensity, maintain relatively stable ecosystem service functions. Therefore, future ecological protection and restoration efforts should prioritise areas with high disturbance intensity and significant declines in ecosystem services, implementing targeted ecological restoration and management measures.

To achieve the sustainable provision of regional ecosystem services, it is essential to strengthen the protection and management of mountainous landscapes, especially in high-disturbance areas such as Gradient IV. Future research should further explore the specific impact mechanisms of different disturbance sources and the long-term ecological effects of human activities in conjunction with natural environments, providing a scientific basis for better balancing regional development and ecological protection.

Future research should focus on integrating real-time remote sensing data and high-resolution spatial datasets to improve monitoring accuracy. Additionally, model calibration and sensitivity analysis should be conducted for local conditions, expanding ecosystem services assessments and integrating socioeconomic factors for a more comprehensive understanding of landscape disturbances and ecosystem management.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Data availability

The data presented in this research are available on request from the corresponding author.

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